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# Simulated Service Testing for Corrosion in Solar Heating and Cooling Systems

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Prepared for:

U.S. Department of Energy  
Office of Solar Applications for Buildings  
Conservation and Renewable Energy  
Washington, DC 20585

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# **SIMULATED SERVICE TESTING FOR CORROSION IN SOLAR HEATING AND COOLING SYSTEMS**

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Paul Wencil Brown  
John W. Grimes, Jr.

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**U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary***  
**NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director***



## ABSTRACT

This study was undertaken to evaluate a proposed ASTM simulated service test methodology to evaluate corrosion or heat transfer liquid degradation. The responses of aluminum, copper, and stainless steel to conditions simulating flow and stagnation in solar collector systems were evaluated. The chemical stabilities of ethylene and propylene glycol solutions at elevated temperatures were also examined.

Key Words: corrosion; elevated temperature; heat transfer liquid degradation kinetics; simulated service test solar collector

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## 1. INTRODUCTION

Among the principal concerns relating to the utilization of active solar systems for space or water heating are those regarding durability. One of the major factors which affect the durability of a solar heating system is the interaction between the heat transfer liquid and its containment system. This interaction may result in changes in the properties of the heat transfer liquid, corrosion of the metallic components of the absorber plate as well as other parts of the containment system, or both. In addition, these phenomena show varying degrees of synergism depending on the compositions of the metal(s) and heat transfer liquid. It is the purpose of this report to describe a test methodology that was used to evaluate the responses of simulated metallic containment systems and heat transfer liquids to a variety of operating and stagnation conditions. This is part of a study to assess the validity of a proposed ASTM accelerated simulated service test methodology.

## 2. TYPES OF TESTS

The test methodologies used in evaluating internal corrosion and heat transfer liquid degradation in solar systems tend to fall into 3 general categories:

- 1) Screening tests
- 2) Simulated service tests
- 3) Field tests.

Screening tests are usually short-term tests in which a metal coupon is placed in contact with a heat transfer liquid and the effect of one or more of the design or operating parameters of a solar systems (usually elevated temperature) is examined. A series of tests of this type have been developed in ASTM Committee E44 on Solar Energy Conversion [1, 2]. Simulated service tests are generally designed to consider most or all of the system design and operating parameters. Field tests involve evaluating a system component or subassembly in service.

### 3. DEFINING DESIGN AND OPERATING PARAMETERS AS A BASIS FOR SIMULATED SERVICE TESTING

The parameters listed in table 1 are among those of importance in affecting the corrosion of a metallic containment system and the degradation of a heat transfer liquid.

The effects of the number of collector cover plates and the use of selective vs. non-selective absorber surfaces on stagnation temperatures is shown in table 2 [3].

In systems which drain, such as swimming pool heaters, stagnation conditions will occur when the absorber is empty except for residual liquid and may result in the concentration of aggressive anions due to evaporation. In non-draining systems, the temperature of the liquid in the absorber may approach the temperatures listed in table 2 should stagnation occur. This, in turn, may cause either oxidative or thermal degradation of the heat transfer liquid.

The geometry of the flow passages will affect the local flow rates, possibly resulting in regions of low flow or turbulence and some flow passage geometries may be conducive to pitting or crevice corrosion. Flow passage geometry will also affect the ratio of the area of internal metal surface to liquid volume.

A collector system may operate at atmospheric pressure under conditions where oxygen is accessible to the liquid, it may operate at atmospheric pressure with an inert gas blanket above the reservoir, or it may operate under pressurization. These operating conditions will affect the degree of liquid aeration.

Dissimilar metal contact is likely in most systems, principally in pumps and valves.

Heat transfer liquids may be aqueous, such as potable water, swimming pool water, or water-glycol mixtures, or non-aqueous such as organic or silicone oils. Heat transfer liquid selection may be based on considerations of toxicity, viscosity which affects pump capacity requirements, chemical stability or inertness, and heat transfer characteristics which affect thermal efficiency. The heat transfer characteristics of the liquid will, in turn, affect the operating temperature, the stagnation temperature, and the temperature differential between the containment system and the heat transfer liquid.

#### 4. DESIGN OF A SIMULATED SOLAR LOOP SYSTEM - DESCRIPTION OF APPARATUS

Cognizant of the design and operating parameters outlined in table 1, several loop systems were constructed to allow evaluation of the effects of continuous flow and stagnation on the corrosion of containment materials or allow evaluation of the stability of heat transfer liquids. Figure 1 is a schematic of these loop systems. The loop systems were designed to allow any metallic containment material or any heat transfer liquid to be tested. In the present case, 12.7 mm (0.5 inch) o.d., 9.5 mm (0.375 inch) i.d., 3003 aluminum alloy tubing, 122 copper alloy tubing, 316 stainless steel tubing were used. With the exceptions of 316 stainless steel flowmeter heads and soldered joints in the copper systems, the flow passages of the loop systems were designed to be constructed entirely of the metal being tested and non-metallic materials.

The overall dimensions of the loops were determined by the internal diameter of the flow passages. To ensure laminar flow across the samples, the minimum length between the sample arrays and bends in a loop leg was 40 times the flow passage diameter.

A typical loop leg is shown in figure 2. Three samples, each 101.6 mm (4 inches) in length, were placed in the center of each leg of the loop. The edge of each sample was machined to accommodate a Viton\* O-ring. This ensured electrical isolation between each sample and the remainder of the loop system. Teflon\* retainers were used to align the samples. These were loosely fitted into aluminum guides. The aluminum guides were interconnected by threaded rods and held in place by stainless steel set screws. This design was selected because it minimizes the direct contact between the samples and the support system. In addition other sample geometries, for example, a section cut from an actual absorber plate could be used.

Four additional aluminum guides were placed on each leg as support points for aluminum sheathing. The sheathing was selected to allow a 3.2 mm (0.125 inch) gap between its internal diameter and the aluminum guides. The sheathing was attached to the tubing support system by set screws, thus minimizing direct contact. Heating tape interspaced with four layers of insulating material was uniformly wrapped around the sheathing. The temperatures at which testing was carried out was controlled by variable transformers and monitored by thermocouples placed along each loop. Testing under stagnation conditions at 90°C indicated that the temperature gradient between the top and bottom of a loop was 2°C thus indicating that relatively uniform heat transfer was achieved.

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\* Certain trade names and company products are identified in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the products are necessarily the best available for the purpose.

Table 1

Solar System Design and Operating Parameters

<u>Design Parameters</u>		<u>Operating Parameters</u>	
i)	Number of covers; selective vs. non-selective absorber surface	i)	Operating and stagnation temperature
ii)	System drains down	ii)	Stagnation, empty or partially full
iii)	System does not drain down	iii)	Stagnation, full
iv)	Geometry of liquid flow passages (crevices, areas of low flow or turbulence, metal surface to liquid volume ratio)	iv)	Flow rate
vi)	Metal selection (dissimilar metal contact)	vi)	---
vii)	Heat transfer liquid selection	vii)	Operating temperature
viii)*	Heat transfer characteristics	viii)	Variable temperature gradients across metal-liquid interface

Table 2\*

Absorber Plate Stagnation Temperatures

One Glass Cover 0.17 $\alpha$ Fe <sub>2</sub> O <sub>3</sub>		Two Glass Covers	
Non-selective	Selective	Non-selective	Selective
143°C	205°C	170°C	219°C

\* T ambient 25°C, Solar radiation 1070 W/m<sup>2</sup>

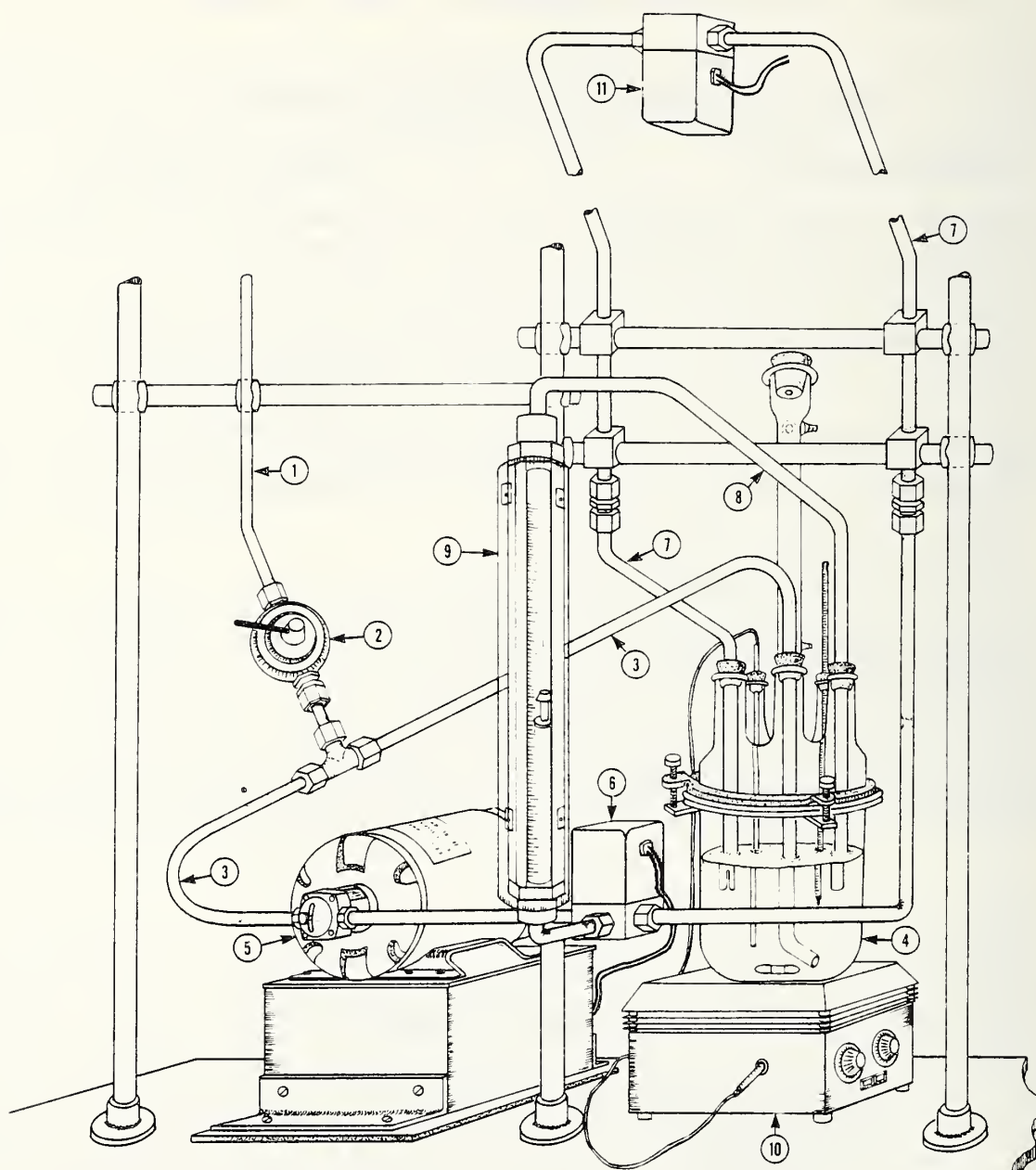


Figure 1. Schematic showing the various components of the loop systems. The systems are initially charged with liquid through the priming port [1] by opening the manual two-way valve [2]. The common flow path [3] is from the reservoir [4], through the pump [5], to the 3-way solenoid valve [6]. The primary flow path [7] is across the samples. The flow path is changed from primary to secondary by activating the 3-way solenoid valve [6] and the secondary path [8] during loop stagnation is through the flowmeter [9]. The hot plate [10] maintains the liquid temperature during stagnation. In systems which stagnate above the boiling point of the liquid, a 2-way solenoid valve [11] placed at the top of the loop is activated during stagnation. In continuous flow systems, a manual 3-way valve replaces the 3-way solenoid valve [6].

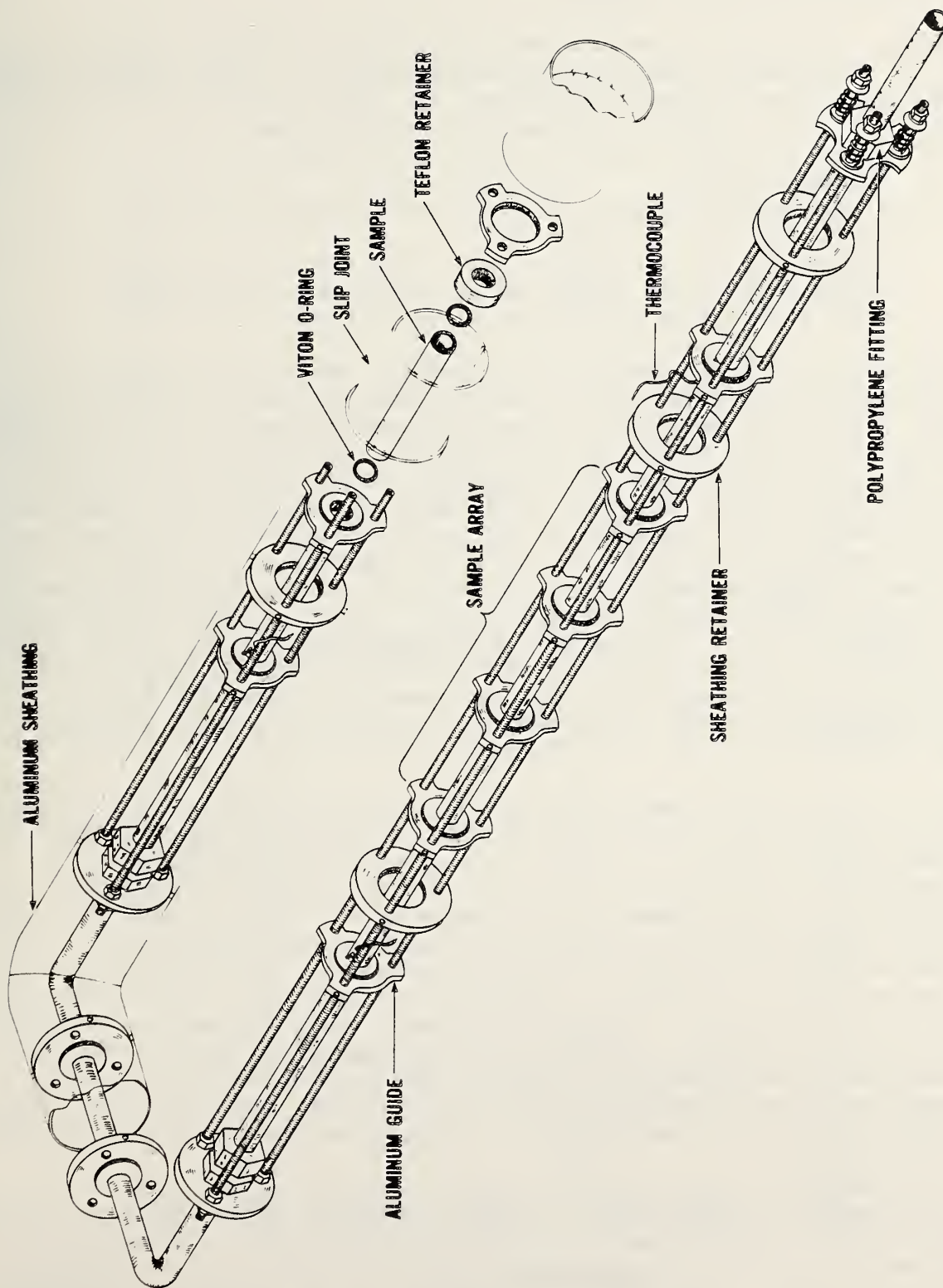


Figure 2. Schematic of a typical loop showing the samples, the sample support system, and the sheathing support system.

## 5. OPERATION OF THE LOOP SYSTEMS

Operating and stagnation temperatures will strongly influence the corrosion rate of a containment system and the decomposition of a heat transfer liquid. Therefore, the loop systems were designed to operate in 3 modes to allow an assessment of these effects. The modes of operation were:

- 1) Continuous flow
- 2) Flow-stagnation cycles at temperatures below the boiling temperature of the liquid
- 3) Flow-stagnation cycles at a flow temperature below the boiling temperature of the liquid and at a stagnation temperature above the boiling temperature of the liquid.

The essential differences between these designs was in the utilization of solenoid valves (see figure 1). In the systems designed for continuous flow, a manual 3-way valve was placed between the pump and the loop. Occasionally this valve was closed to the loop and opened to the flowmeter to observe the flow rate. In the systems with a stagnation cycle, a 3-way solenoid valve was placed in a similar location. This valve was connected to a timer-cycler which allowed it to be activated on any preset cycle. When this valve was activated the flow of liquid to the loop was diverted and a column of liquid was trapped in one leg while the other leg drained resulting in stagnant full and stagnant empty conditions, respectively. In the systems which stagnated at a temperature above the boiling temperature of the liquid, a 2-way solenoid valve placed at the top of the loop and activated simultaneously with the 3-way valve. The flow-stagnation cycle used was 4 hours of flow followed by 4 hours of stagnation. The flow temperature used was 90°C while stagnation temperatures were 90, 120, or 135°C.

Figure 3 shows a time temperature profile typical of a system which stagnates at 120°C. At time  $t_0$ , heat transfer liquid is flowing through the loop and the temperature is 90°C. At time  $t_1$ , the power to the heating tapes is switched off by deactivating the two variable transformers which control the flow temperature. The temperature decreases until time  $t_2$  is reached. The variable transformers which control the stagnation temperature and the solenoid valves which determine the flow path and isolate the stagnant-full loop leg (valves 6 and 11 in figure 1) are activated at time  $t_2$ . The temperature begins to rise to 120°C. Stagnation continues to time  $t_3$  when the solenoid valves open, the variable transformers controlling the stagnation temperature are deactivated and those controlling the flow temperature are activated. The temperature drops rapidly as 70°C liquid from the reservoir flows through the loop, reaching a minimum at time  $t_4$ . The temperature then rises to 90°C as flow continues.

An electromechanical schematic of the loop systems is shown in figure 4. The durations of the flow-stagnation cycles were controlled by a timer-cycler which consisted of three microswitches and three cams driven by a timer motor geared to 0.25 rph. Microswitch No. 1 controlled the opening and closing of the three-way solenoid valve, labelled valve #6, which controlled the heat transfer liquid flow path. Microswitch No. 2 controlled the activation of

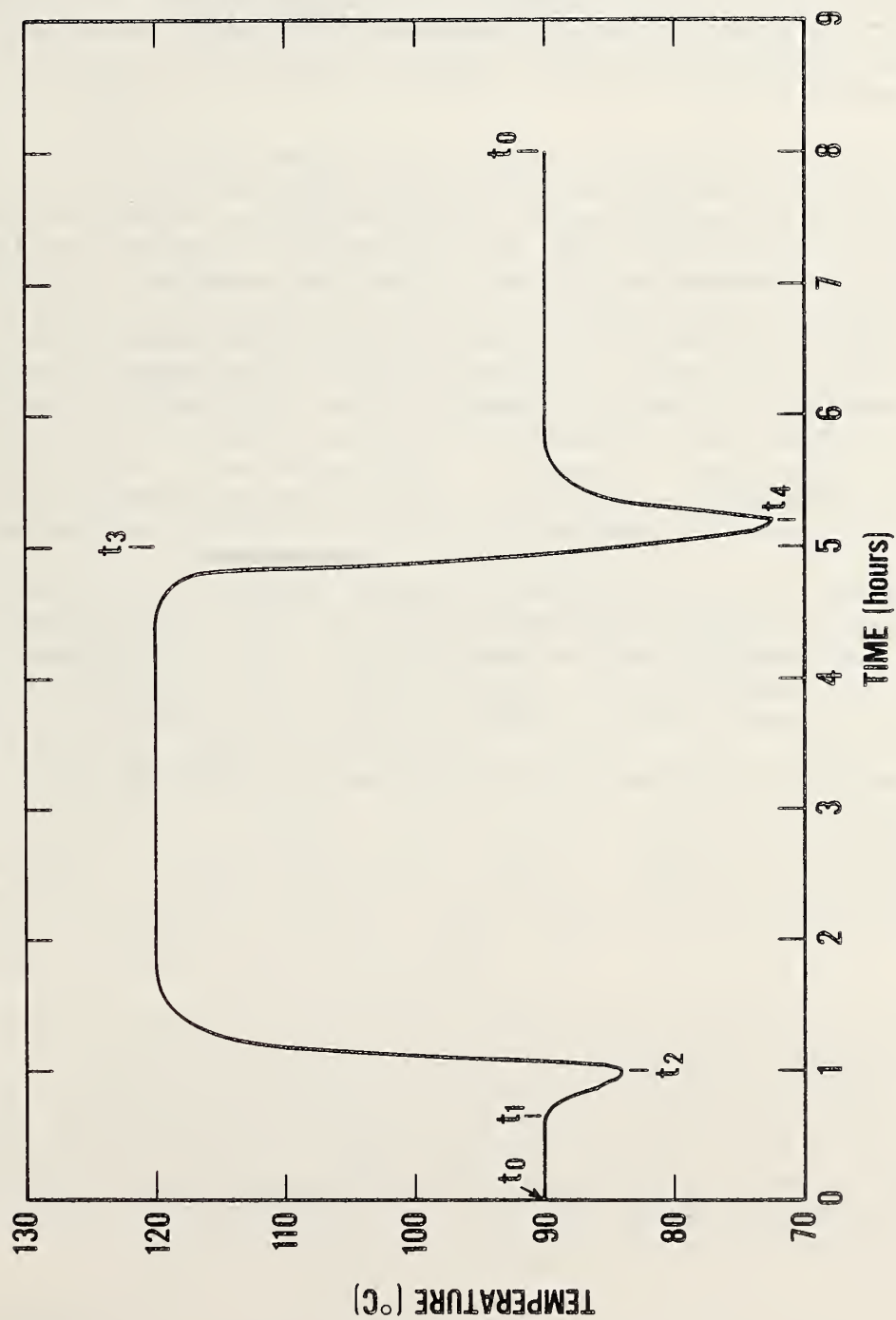


Figure 3. Time-temperature profile of a system which stagnates at 120°C.

the heating tapes. This was done by activating two power relays each of which interfaced between two variable transformers and the heating tapes. The heating tapes on each leg of the loop were powered independently. It was necessary to design the system in this way in order to maintain the desired flow and stagnation temperatures on each loop leg. A total of four variable transformers were used. Two were used to set the flow temperatures while the other two were used to set the stagnation temperatures. Microswitch No. 3 was used to activate the two-way solenoid valve, labelled valve #11. This valve was used in systems which stagnated above the boiling point of the heat transfer liquid.

The cam system activated the three microswitches slightly out of phase. This along with a time delay relay was used to minimize the temperature excursions which occurred in going from the flow modes to the stagnant modes (see figure 3). The variable transformers which controlled the stagnation temperatures were deactivated about 30 minutes before flow commenced. This allowed the heat transfer liquid to cool to below its boiling point prior to the initiation of flow. The three-way valve was set to open a few minute after two-way valve opened and to close a few minutes before the two-way valve closed. This was accomplished by using a time delay relay. Because the power required to maintain the stagnation temperature was lower than that required to maintain the flow temperature, the variable transformers which controlled the flow temperature were set to deactivate and those which controlled the stagnation temperature set to activate about 15 minutes before stagnation began.

The internal volumes of the loop systems were approximately 390 ml and the internal surface areas approximately 650 cm<sup>2</sup>. The liquid volume to internal surface area was maintained at approximately 3 by charging each system with 2000 ml of liquid. Two-liter, glass reaction vessels were used as reservoirs. Hot plates placed under each reservoir were used to maintain the temperature of the liquid in the reservoirs at 70°C during stagnation cycles. Flow rates were controlled by variable speed pumps and were maintained at 0.64 m/s (2.5 ft/s).

## 6. HEAT TRANSFER LIQUID STABILITY

Prior to constructing the loop systems, a series of tests were carried out to examine the stabilities of ethylene glycol and propylene glycol. These tests were carried out at 100°C in the presence of aluminum and copper under conditions of aeration and deaeration. This was done in order to separate the effects of thermal and oxidative decomposition of these liquids while bracketing the degree of aeration likely to occur in the loop systems and to examine changes in the liquids as a function of time as a basis for determining a reasonable test duration.

Reagent grades ethylene and propylene glycol were diluted to 50 volume percent with ASTM D1384 water [4]\*. These solutions were placed in round bottomed flasks and weighed coupons of 1100 aluminum or 110 copper alloys were placed in the solutions. The flasks were heated to 100°C and the solutions either deaerated with high purity N<sub>2</sub> or aerated with laboratory air. No provision was made to remove carbon dioxide in the aeration experiments. Aliquots of liquid were removed biweekly for analysis and after 16 weeks the tests were terminated and the coupons reweighed and visually inspected. The experimental details and the results of this study are presented in table 3.

Figure 5 shows the apparatus used in these experiments. This consisted of a 3-necked, round bottom, flask which contained the test solution. A gas dispersion tube was inserted in one neck, a condenser tube in the second, and the third neck, which was used for sampling, was stoppered. The temperature of the solution within the flask was held constant within  $\pm 1^\circ\text{C}$  by using a double boiler arrangement. The round bottom flask was suspended in a specimen jar containing a polyglycol heat transfer liquid. The temperature of this liquid was maintained using a controlled temperature hot plate.

Based on the assumption that the degradation of ethylene and propylene glycol results in the generation of acidic reaction products, variation in solution pH with time was used as a measure of the degree of degradation. Under aeration conditions pH changes may result from both oxidative and thermal decomposition of the liquid. Further, the presence of metals may in some measure catalyze liquid decomposition. Under conditions of deaeration, oxidative liquid decomposition is minimized.

Figure 6 shows the variation of solution pH over time for aerated solutions of ethylene and propylene glycol held at 100°C. This figure indicates that propylene glycol to show significantly greater stability than ethylene glycol under aeration conditions when no metal is present. The rapid initial increase in pH observed in this figure appeared to occur in all of the experiments regardless of the solution composition, the presence of metal, and regardless of extent of liquid aeration. While the precise reason for the

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\* ASTM D1384 water contains NaCl, Na<sub>2</sub>SO<sub>4</sub> and NaHCO<sub>3</sub> at concentrations of 100 ppm.

Table 3

SUMMARY OF GLYCOL STABILITY STUDYExperimental Conditions

Temperature	100°C
Solution Composition	50% ASTM D1384 water and reagent grade ethylene glycol or propylene glycol
Solution Volume	700 ml
Metals Used	110 Cu or 1100 Al alloys
Nominal Metal Coupon Dimensions	2 x 3 x 0.003 inches (50.8 x 76.2 x 0.076 mm)
Aeration Conditions	Laboratory compressed air or purified N <sub>2</sub>
Test Duration	16 weeks

Experimental Results

<u>Solution</u>	<u>Metal</u>	<u>Aeration Condition</u>	<u>Appearance after Test</u>
Ethylene glycol	Cu	air	Total dissolution, blue ppt
Ethylene glycol	Cu	N <sub>2</sub>	Light tarnish
Propylene glycol	Cu	air	Virtually total dissolution, green ppt
Propylene glycol	Cu	N <sub>2</sub>	Light tarnish
Ethylene glycol	Al	air	White film
Ethylene glycol	Al	N <sub>2</sub>	White film
Propylene glycol	Al	air	Black film
Propylene glycol	Al	N <sub>2</sub>	White film

# TIMER-CYCLER

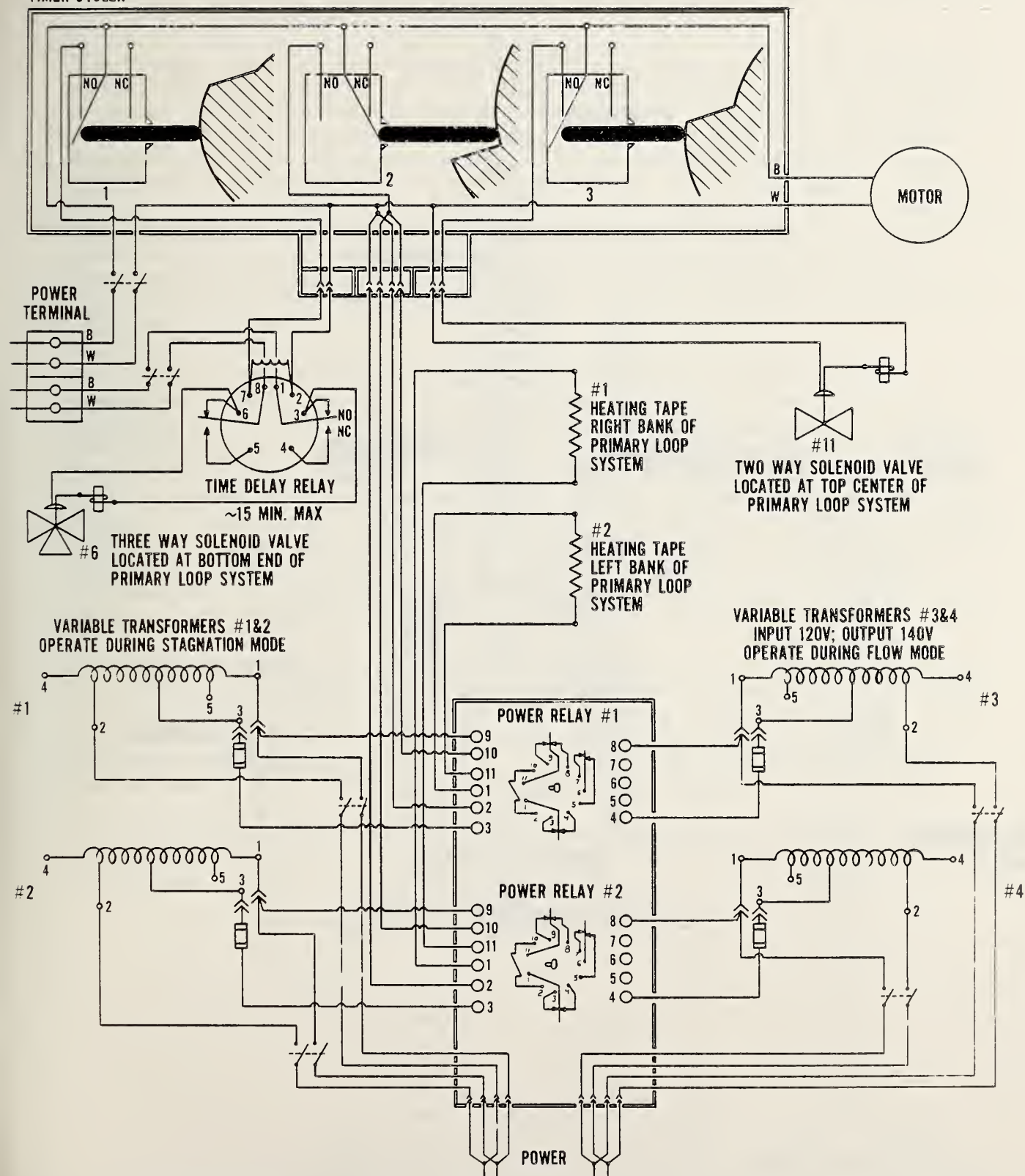


Figure 4. Electromechanical schematic of the loop systems.

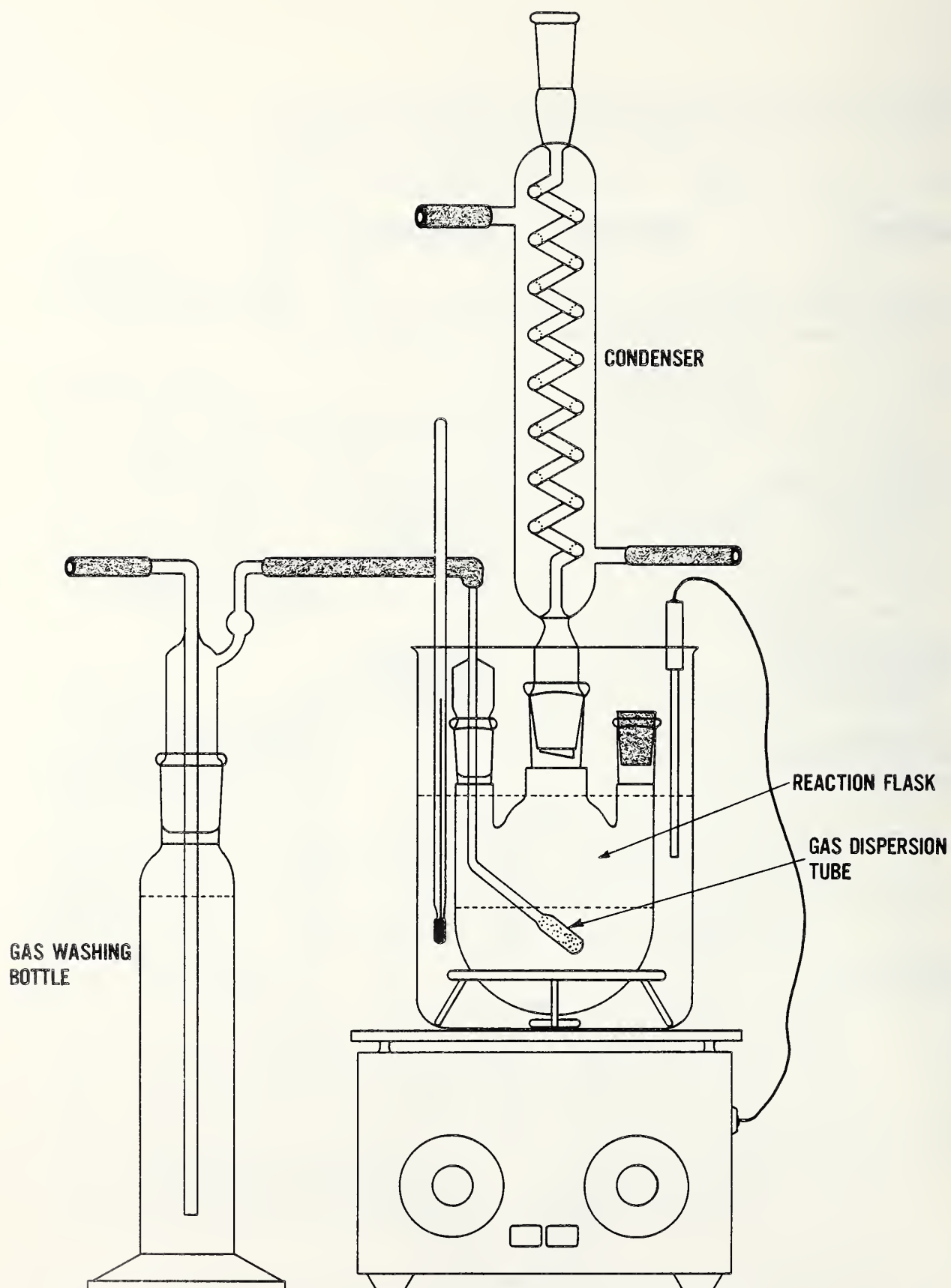


Figure 5. Schematic of the apparatus used to study the degradation of ethylene and propylene glycol.

initial pH increase is unknown, it may be related to the loss of atmospheric CO<sub>2</sub> from the solutions upon heating.

The thermal aspect of the chemical stability of these glycols was examined by maintaining the solutions at 100°C while deaerating with purified nitrogen to minimize the availability of oxygen. Aluminum and copper foils were immersed in the solutions to examine whether the presence of these metals affected degradation. Figure 7 shows the pH variations which occurred under these experimental conditions. The overall variations in pH were small in comparison to those observed under aeration conditions indicating that the availability of oxygen is a major factor in affecting glycol degradation. Further, while ethylene glycol solutions appear to be thermally more stable than propylene glycol solutions, the presence of copper reduces the thermal stability of both ethylene and propylene glycol solutions relative to that when aluminum is present.

The effect of the presence of copper and aluminum on pH under aeration conditions is shown in figure 8. The presence of copper resulted in rapid decreases in pH in both the ethylene glycol and propylene glycol solutions. The ethylene glycol solution in contact with aluminum also showed a substantial decline in pH. However, the change of pH of the propylene glycol solution in contact with aluminum was about the same as that which occurred under deaeration conditions. Thus, both the presence of copper metal and the availability of oxygen accelerate the degradation of ethylene and propylene glycol while the affect of the presence of aluminum is minimal. Further, while ethylene glycol appears thermally slightly more stable than propylene glycol, it is significantly less oxidatively stable.

The kinetics of these degradation reactions could not be rigorously expressed by a kinetic equation of any definite order and in some instances it appears that the kinetic order of the degradation reaction changes with time. This is shown in figure 7 where it appears that ethylene glycol degradation approximates a reaction first order in H<sup>+</sup> while that of propylene glycol approximates a first order reaction after about 7 weeks.

In spite of this, these data do qualitatively indicate the relative oxidation and thermal stabilities of ethylene and propylene glycol under various conditions.

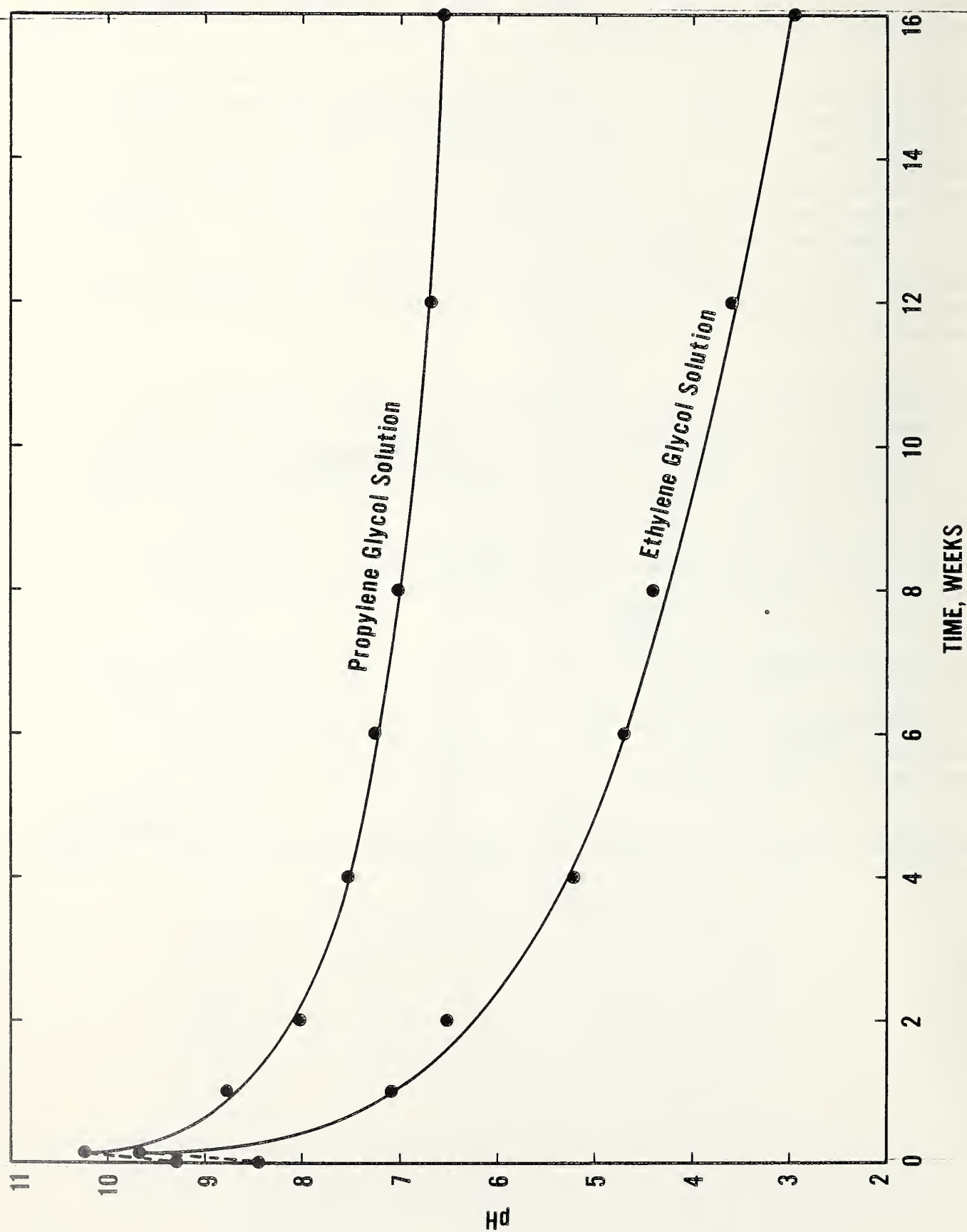


Figure 6. Plots of solution pH vs. time for aerated solutions of ethylene and propylene glycol at 100°C.

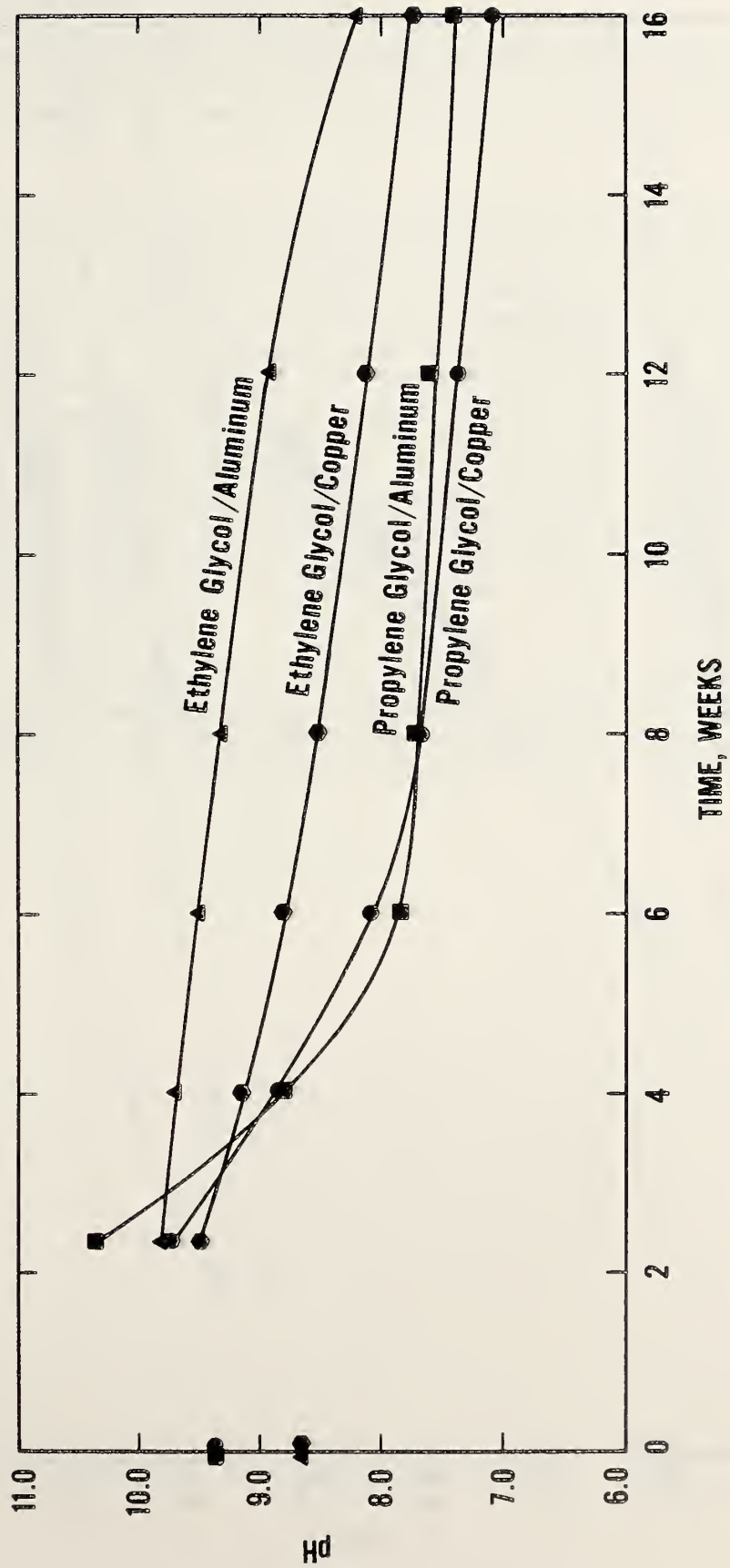


Figure 7. Plots of solution pH vs. time for deaerated solutions of ethylene and propylene glycol in contact with aluminum and copper at 100°C.

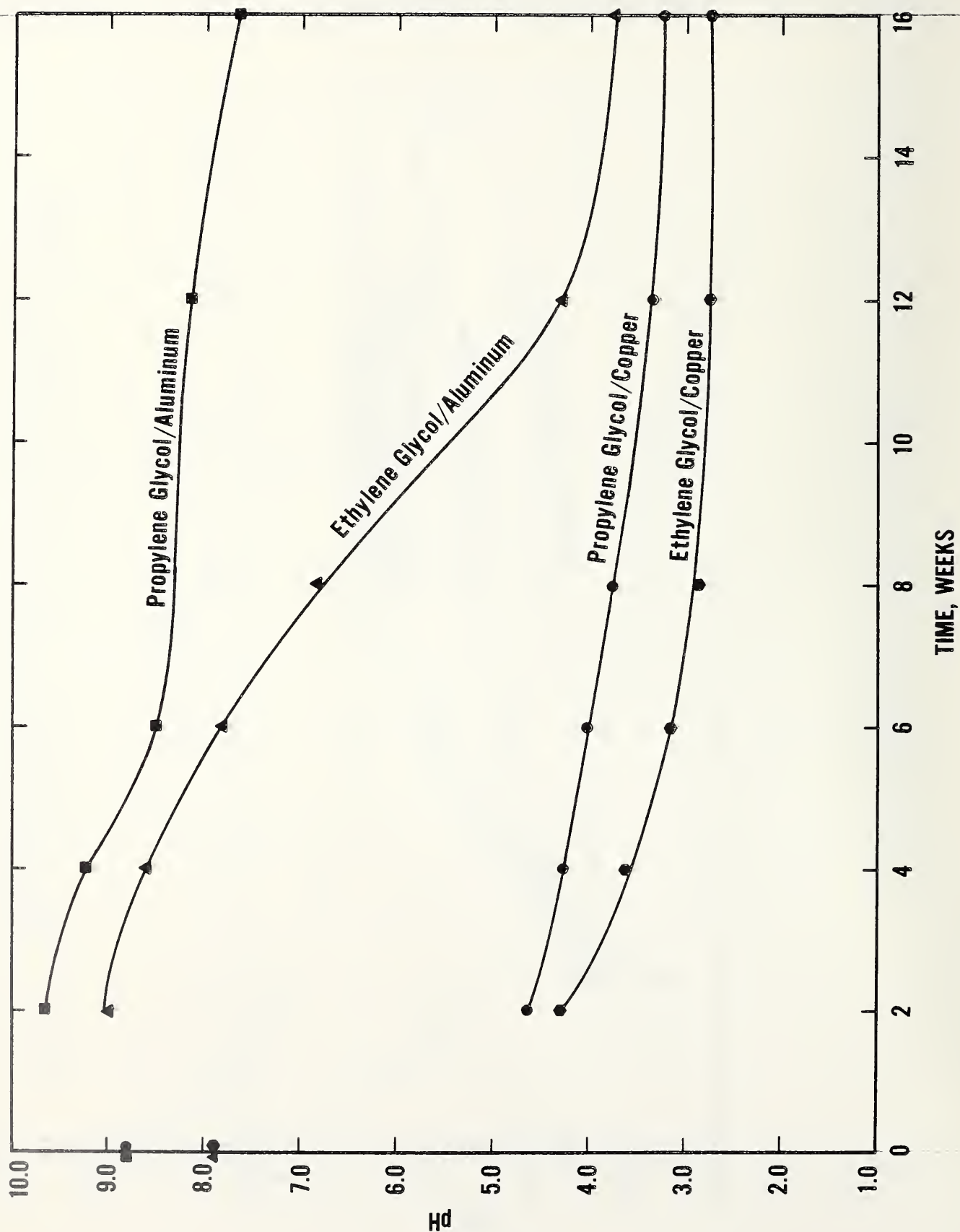


Figure 8. Plots of solution pH vs. time for aerated solutions of ethylene and propylene glycol in contact with aluminum and copper at 100°C.

## 7. SIMULATED SERVICE TEST CONDITIONS

A total of seven simulated service tests were carried out. Four were conducted in aluminum systems, two in copper systems and one in a stainless steel system. A summary of the test conditions used is presented in table 4.

Based on the results of the heat transfer liquid stability tests, ethylene glycol based heat transfer liquids were used in the aluminum and copper systems. Ethylene glycol was selected because it was found to be less stable than propylene glycol in the presence of oxygen and aluminum at the operating temperatures of the loops. Some heat transfer liquid degradation was desired in this instance in order to allow an assessment of the effects of the test conditions after a reasonable test duration. The heat transfer liquid used in the aluminum systems was a mixture of 50 volume percent of reagent grade ethylene glycol and 50 volume percent ASTM D1384 water [4]. Due to the interaction of copper with ethylene glycol observed in the heat transfer liquid stability tests, a mixture of 25 volume percent reagent grade ethylene glycol, 25 volume percent buffered and inhibited standard antifreeze solution [5], and 50 volume percent ASTM D1384 water was used in the copper systems. The heat transfer liquid used in the stainless steel system was distilled water containing 1000 ppm of NaCl.

The flow temperatures were maintained at 90°C and flow rates of 0.64 m/s. were used in all systems. The stagnation temperatures used were 90°C, 120°C, or 135°C. The tests were carried out for 112 days (16 weeks) in the aluminum and stainless steel systems and for 168 days (24 weeks) in the copper systems.

Table 4

Summary of Test Conditions

Alloy	System	Other Materials Exposed to the Heat Transfer Liquids	Heat Transfer Liquids	Temperature		Flow Rate	Test Duration
				Flow	Stagnation		
3003 Al	Al #1	Teflon, epoxy,	Ethylene glycol 50%,	90°C	--	0.64 m/sec	16 weeks
	Al #2	polyethylene,	ASTM D1384	90°C	90°C	"	"
	Al #3	glass, 316	water 50%	90°C	120°C	"	"
	Al #4	stainless steel		90°C	135°C	"	"
122 Cu	Cu #1	Above and 95/5	Ethylene glycol, 25%	90°C	--	0.64 m/sec	24 weeks
	Cu #2	Sn/Sb solder	GM 6038-M, Type A antifreeze 25% ASTM D1384 water 50%	90°C	120°C	"	24 weeks
316 S/S	S/S #1	Teflon, epoxy, polyethylene, pyrex glass	Distilled water +1000 ppm NaCl	90°C	120°C	0.64 m/sec	16 weeks

## 8. SIMULATED SERVICE TEST RESULTS

Copper system number 1 operated under conditions of continuous flow at 90°C for 24 weeks. The solution pH was 8.20. The initial and final reserve alkalinity values as measured by ASTM D1121 [6] were 3.89 and 3.56, respectively. The average corrosion rate of the 6 specimens tested in this system was 0.03 mpy.

Copper system number 2 operated on a cycle of 4 hours of flow at 90°C and 4 hours of stagnant at 120°C. The duration of this test was 24 weeks. The solution pH was 8.20. The initial and final reserve alkalinity values were 3.89 and 3.05, respectively. The average corrosion rate of the 3 specimens on the stagnant full side of the loop was 0.08 mpy and that of the three specimens on the stagnant empty side was 0.12 mpy.

The stainless steel system often operated on a cycle of 4 hours of flow at 90°C and 4 hours of stagnation at 120°C. In this system both sides of the loop stagnated empty. The duration of this test was 16 weeks. The initial solution pH was 7.72 and the final solution pH was 8.57. The corrosion rates of the stainless steel specimens were negligible.

Aluminum system number 1 operated under conditions of continuous flow at 90°C for 16 weeks. The initial solution pH was 8.38 and the final solution pH was 5.56. The average corrosion rate of the 6 specimens tested in this system was 0.49 mpy. The presence of pitting was observed to be uniformly distributed among the specimens. The maximum pit depth observed was 1.06 mm. The average of the 10 deepest pits observed was 0.93 mm.

Aluminum system number 2 operated on a cycle of 4 hours of flow at 90°C and 4 hours of stagnation at 90°C. The duration of this test was 16 weeks. The initial and final solution pH values were 8.38 and 5.08, respectively. The average corrosion rate of the 3 specimens on the stagnant full side of the loop was 0.40 mpy while that of the specimens on the stagnant empty side was 0.38 mpy. Negligible pitting was observed in these specimens.

Aluminum system number 3 operated on a cycle of 4 hours of flow at 90°C and 4 hours of stagnation at 120°C. The duration of this test was 16 weeks. The initial solution pH was 8.38 and the final solution pH was 5.33. The average corrosion rate of the 3 specimens on the stagnant full side was 0.28 mpy while that of the specimens on the stagnant empty side was 0.54 mpy. The pits observed in the specimens on the stagnant empty side were both more numerous and deeper than those observed on the stagnant full side. Maximum pit depths on the stagnant empty and stagnant full sides were 0.85 and 0.55 mm, respectively. Similarly, the averages of the 10 deepest pits were 0.72 and 0.46 mm, respectively.

Aluminum system number 4 operated on a cycle of 4 hours of flow at 90°C and 4 hours of stagnant at 135°C. The duration of this test was 16 weeks. The initial solution pH was 8.38 and the final solution pH was 5.64. The average corrosion rate of the 3 specimens on the stagnant empty side was 1.34 mpy. The average corrosion rate of the 3 specimens on the stagnant full side was

0.67 mpy. Minimal pitting was observed in these specimens. Pitting on the stagnant full side was negligible. Pitting was observed in 2 of the 3 specimens on the stagnant empty side and the maximum pit depth was 0.12 mm. Only 6 pits were observed in total and their average depth was 0.09 mm.

Table 5 summarizes the results presented in this section.

Table 5  
Summary of Test Results

System	T, °C		pH		Corrosion Rate, mpy		Deepest Pit	
	Flow/Stag.		Initial	Final	Empty Side	Full Side	Empty Side	Full Side
Al #1	90	-	8.35	5.56	0.49		1.06 mm	
Al #2	90	90	"	5.08	0.38	0.40	negl.	negl.
Al #3	90	120	"	5.33	0.54	0.28	0.85	0.55
Al #4	90	135	"	5.64	1.34	0.67	0.12	negl.
Cu #1	90	-	Reserve Alk. 3.89 3.56		0.03			
Cu #2	90	120	3.89	3.05	0.12	0.08		
S/S	90	120	7.72	<sup>pH</sup> 8.57	negligible			

## 9. DISCUSSION OF TEST RESULTS

The responses of both the aluminum and the copper specimens tested under the various conditions differed depending on the nature of the test conditions imposed.

The corrosion rates in both copper systems were low. However, operation on the flow stagnation cycle (copper system number 2) was more conducive to corrosion than was continuous flow (copper system number 1). The severity of corrosion, as measured by mass loss, ranked as follows:

Cu 1 < Cu 2, stagnant full side < Cu 2, stagnant empty side

This may be the result of the effects of temperature in that copper system number 2 showed the higher corrosion rates. In addition, the corrosion rate on the stagnant empty side of copper 2 was higher than on the stagnant full side. This may be the result of the concentration of aggressive species during each stagnation cycle as water evaporated from the heat transfer liquid remaining after this side of the system has drained.

The initial and final heat transfer liquid reserve alkalinities paralleled the corrosion behavior in the copper systems. The reserve alkalinity of copper system number 1 decreased by 8% while that of copper system number 2 decreased by 22%.

The test carried out using 316 stainless steel specimens was inconclusive. A slight rise in solution pH was observed. However, mass measurements indicated negligible loss and pitting was not observed.

The four aluminum systems were operated using an uninhibited, unbuffered heat transfer liquid and the corrosion rates were correspondingly higher. The corrosion rates on the stagnant empty sides of the three aluminum systems which operated on flow-stagnation cycles increased with increasing stagnation temperature.

The corrosion rates on the stagnation full sides of systems 3 and 4 were one half of the respective corrosion rates on the stagnant empty sides of these systems. However, the corrosion rate on the stagnant full side of system 2 was comparable to that on the stagnant empty side. System 2 stagnated below the boiling temperature of the heat transfer liquid while systems 3 and 4 stagnated above the boiling temperature of the heat transfer liquid. The slightly elevated corrosion rate on the stagnant full side in system 2 may therefore be related to the degree of aeration of the liquid during stagnation. Similar behavior has been observed for 1100 Al in distilled water [7]. The corrosion rate in aluminum system number 1, which operated under conditions of continuous flow was higher than those in the stagnant full sides of systems 2 and 3. Only when stagnation full occurred at 135°C did the corrosion rate exceed that of continuous flow at 90°C.

The nature of the corrosion observed in the aluminum systems also varied with the test conditions. Pitting corrosion appeared to be the dominant

corrosion mechanism in systems 1 and 3. The pitting factors calculated for these systems ranged from 200 to 280. Alternatively, negligible pitting was observed in system 2. Similarly, negligible pitting was observed on the stagnant full side of system 4 while only minimal pitting occurred on the stagnant empty side of this system. Comparison of mass loss and pitting data indicate the predominant mode of corrosion in the aluminum systems to change from pitting corrosion to general corrosion in an inconsistent manner.

## 10. ACKNOWLEDGMENT

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11. ABSTRACT <i>(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)</i>  This study was undertaken to evaluate a proposed ASTM simulated service test methodology to evaluate corrosion or heat transfer liquid degradation. The responses of aluminum, copper, and stainless steel to conditions simulating flow and stagnation in solar collector systems were evaluated. The chemical stabilities of ethylene and propylene glycol solutions at elevated temperature were also examined.			
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